J^{π} and multipolarity assignments in (HI,xnypzαγ) reactions

B. Singh and J.C. Waddington
Department of Physics and Astronomy
McMaster University, Hamilton, Ontario, L8S 4M1 Canada
(June 4, 2001)

In heavy-ion compound nuclear experiments (HI,xnypzαγ), the multipolarity of the γ transitions and the relative spin and parities of the levels are generally determined through the measurement of angular distributions, angular correlations and linear polarizations of γ-rays, and through measurement of internal conversion coefficients.

Angular distributions

1. The angular distributions of γ-rays, $W(\theta)$, is a measurement of the intensity as a function of the angle θ with respect to the beam direction or to the nuclear spin axis.

$$W(\theta) = \sum_{K \text{ even}} A_K P_K(\cos\theta)$$

2. The values of the A_2 and A_4 coefficients depend on ΔJ, the mixing ratio (δ(L+1)/L) and the degree of alignment. For high-spin states the distributions are largely independent of spin.
3. The degree of alignment, σ/J, is usually determined through a measurement of $W(\theta)$ for a number of known ΔJ = 2 transitions. In actual practice many authors use σ/J = 0.3 for the degree of alignment. Here σ = half-width of the Gaussian describing the magnetic sub-state population. The attenuation caused by the degree of alignment affects only the magnitudes of A_2 and A_4. Level lifetimes are assumed to be small so that alignment is maintained.
4. Angular distribution measurements alone may be used to deduce ΔJ but not Δπ.
5. Typical values of A_2 and A_4 are given in the table below (σ/J = 0.3 assumed).

The angle θ is measured relative to the beam direction. If θ were with respect to spin axis, then sign of A_2 is generally reversed.

Table of Angular Distributions

ΔJ	Multipolarity	Sign of A_2	Sign of A_4	Typical Values A_2	A_4
2	Quadrupole	+	-	+0.3	-0.1
1	Dipole	-		-0.2	0.0
1	Quadrupole	-	+	-0.1	+0.2
1	Dipole + quadrupole	+ or -	+	+0.5 to -0.8	0.0 to +0.2
0	Dipole	+		+0.35	0.0
0	Quadrupole	-	-	-0.25	-0.25
0	Dipole + quadrupole	+ or -	-	+0.35 to -0.25	0 to -0.25

Angular correlations (or DCO, directional correlations of γ-rays from oriented states of nuclei)

6. DCO measurements involve the determination of the coincidence intensities for two γ-rays, one of known multipolarity γ_K, and the other of unknown multipolarity γ_U. The γ-rays are detected at two angles, θ_1 and θ_2, with respect to the beam direction. The coincidence intensities are determined as two-dimensional areas, $I(\theta_1\theta_2\gamma_K\gamma_U)$ and $I(\theta_1\theta_2\gamma_U\gamma_K)$, where in the former case γ_K is detected at angle θ_1 and γ_U at angle θ_2.

The DCO ratios are then defined as

$$R = I(\theta_1\theta_2\gamma_K\gamma_U) / I(\theta_1\theta_2\gamma_U\gamma_K)$$

7. As with angular distributions, these ratios are insensitive to spin for high spin states but are sensitive to relative spins and multipolarities.
8. The angles θ_1 and θ_2 are generally determined by the geometry of the array. The values of R given below are typical for an array with detectors at 37° and 79°. An alignment of $\sigma/J = 0.3$ has been assumed.

Table of typical DCO ratios

ΔJ_γ^{gate}, Multipolarity	ΔJ_γ	Multipolarity	Typical R(DCO)
2, quadrupole	2	Quadrupole	1.0
2, quadrupole	1	Dipole	0.56 (θ_1=37°,θ_2=79°)
2, quadrupole	1	Dipole + quadrupole	0.2 to 1.3 (θ_1=37°,θ_2=79°)
2, quadrupole	0	Dipole	1.0
2, quadrupole	0	Dipole + quadrupole	0.6 to 1.0 (θ_1=37°,θ_2=79°)
1, dipole	2	Quadrupole	1/0.56 (θ_1=37°,θ_2=79°)

1, dipole	1	Dipole	1.0
1, dipole	0	Dipole	~1/0.56

Linear polarization of γ-rays

9. A Compton polarimeter apparatus allows the measurement of relative intensities of radiation scattered in planes perpendicular to and parallel to the reaction plane (plane defined by the beam direction and incident gamma ray).

10. Determination of γ-ray polarization may differentiate between electric and magnetic radiations and combined with correlation data allows determination of $\Delta\pi$. See Kim et al.

Internal conversion coefficient data

11. Conversion coefficients or subshell ratios may be obtained from electron spectra or from γ-ray intensity balances.

12. The interpretation of internal conversion coefficient data is as given in earlier rules in NDS for spin and parity assignments. Note that electron data usually give K-, L- ... conversion coefficients or sub-shell ratios whereas intensity balance arguments give total conversion coefficients

Other considerations:

13. If $T_{1/2}$ (level) is known or a limit can be assumed (based on coincidence resolving time, for example), RUL (recommended upper limits for Weisskopf estimates) may serve to eliminate the M2 option for a $\Delta J = 2$ quadrupole

transition.

14. Generally for the states populated in high-spin reactions, spins increase with increasing excitation energy. This is a result of the fact that these reactions tend to populate yrast or near yrast states.

15. For a well-deformed nucleus, when a regular sequence of $\Delta J=2$ (stretched quadrupole) transitions is observed at high spins as a cascade, then the sequence may be assigned to a common band with E2 multipolarity for all the transitions in the cascade. A similar but somewhat weaker argument holds for less deformed nuclei where a common structure of levels is connected by a regular sequence of $\Delta J=2$ (stretched transitions) as a cascade. For interband transitions, $\Delta J = 1, 0$ transitions with significant admixtures are considered to be of M1 + E2 type. If the transition is pure dipole ($\delta(Q/D)=0$), it is quite often E1. The small deformation Magnetic-rotational (M1) bands present exceptions to this rule.

16. The presence of strongly coupled (deformation alignment) bands allows assignment of relative spins and parities of the band members. The presence of a measurable quadrupole admixture in the $\Delta J = 1$ cascading transitions is required to prove that all the states have the same parity. This is because nuclei with octupole deformation may be two rotational $\Delta J = 2$ sequences of opposite parity connected by cascading E1 transitions.

17. For near-spherical nuclei, when a regular sequence of $\Delta J=1$ (stretched dipole) transitions is observed at high spins as a cascade, then the sequence may be assigned to a common band with M1 multipolarity for all the

transitions in the cascade. (Cascades of $\Delta J=1$, E1 transitions occur in rare cases of nuclides which show alternating-parity bands or reflection asymmetry.)

18. In the absence of angular distribution/correlation data, a regular sequence of transitions in a cascade may be assigned to a common structure or a band if:
    1) The low-lying levels of this structure have well established spin parity assignments.
    2) If there is good evidence that, at higher energies and spins, the band has not changed in its internal structure due to band crossings or other perturbations.
19. In strongly coupled bands, (deformation aligned) a comparison of experimentally deduced value of g_K (from mixing ratio δ(E2/M1) and assumed g_R and Q_O) with that calculated on the basis of a proposed quasi-particle configuration may lead to the assignment of parity to a band.
20. A comparison of experimental and calculated Routhians and particle alignments (from cranked shell-model calculations) for suggested quasi-particle configurations may give information about the parity of a rotational band.

References for $\gamma(\theta)$, $\gamma\gamma(\theta)$(DCO), γ (linear polarization):

1. Yamazaki, T., Nucl. Data Tables **A3**, 1 (1967). :$\gamma(\theta)$
2. Der Mateosian E. and Sunyar A.W., At. Data and Nucl. Data Tables, **13**, 391 (1974); ibid. 407 (1974). :$\gamma(\theta)$
3. Taras, P. and Haas, B., Nucl. Instr. Methods **123**, 73 (1975). :$\gamma(\theta)$ (Sign of mixing ratio (Q/D) in this paper is opposite to that used in ENSDF. :$\gamma\gamma(\theta)$(DCO)
4. Ekstrom, L.P. and Nordlund, A., Nucl. Instr. Methods **A313**, 421 (1992).
5. Kramer-Flecken, A., *et al*., Nucl. Instr. Methods **A275**, 333 (1989). :$\gamma\gamma(\theta)$(DCO)
6. Aoki, T. *et al.*, At. Data Nucl. Tables, **23**, 349 (1979). γ(Lin Pol.)
7. Kim, J.S., *et al*., Phys. Rev. **C12**, 499 (1975). γ(Lin Pol.)
8. Krane, K.S., Steffen, R.M. and Wheeler, R.M., Nuclear Data Tables **A11**, 351 (1973) :$\gamma\gamma(\theta)$(DCO)